High Temperature Alloys

Pushing the Limits

Heat Resistant Alloys

- Brief Review of Wrought & Cast Heat Resistant Alloys
- Alloy Developments
  - 2nd & 3rd Stage Developments
- Most Recent Alloy Developments
- Hurdles for Greater Utilization

Heat Resistant Alloys

- Alloys used for temperatures above 1000°F
- Major Alloying Elements
  - Iron
    - Typically 8-75%
  - Chromium
    - Typically 15-25%
  - Nickel
    - Typically 8-80%

In the Beginning
1st Generation (Pre-1960)

- Wrought
  - 309 Stainless Steel
  - 310 Stainless Steel
  - RA330 Alloy
  - Inconel® 600 alloy
- Cast
  - HK-40
  - HT or HU
  - HX

We Need Stronger Materials

- Resistance to Creep
- Resistance to Distortion

Second Generation (1960-1980)

- Wrought
  - Inconel 601
    - Higher Cr w/ Aluminum for Oxidation
  - Incoloy 800H & HT
    - Al + Ti, Coarse Grains for Strength
  - Hastelloy X
    - Mo, Co, W additions for Strength
  - RA333
    - Co, W, Mo, additions for Strength
    - High Cr, Silicon for Oxidation
- Castings
  - HP Modified (W)
    - Supertherm
    - Thermalloy 63W
    - Thermax 63WC
    - MO-RE 1
  - 22H
  - Super 22H

Increased Efficiency
Latest Generation (1980 – Today)

- Increased Oxidation Resistance
  - Improved Operating Efficiency
    - Operating Temperatures Increase
  - Thinner Sections
    - Need to Reduce Metal Loss
- Further Strength Increases Needed

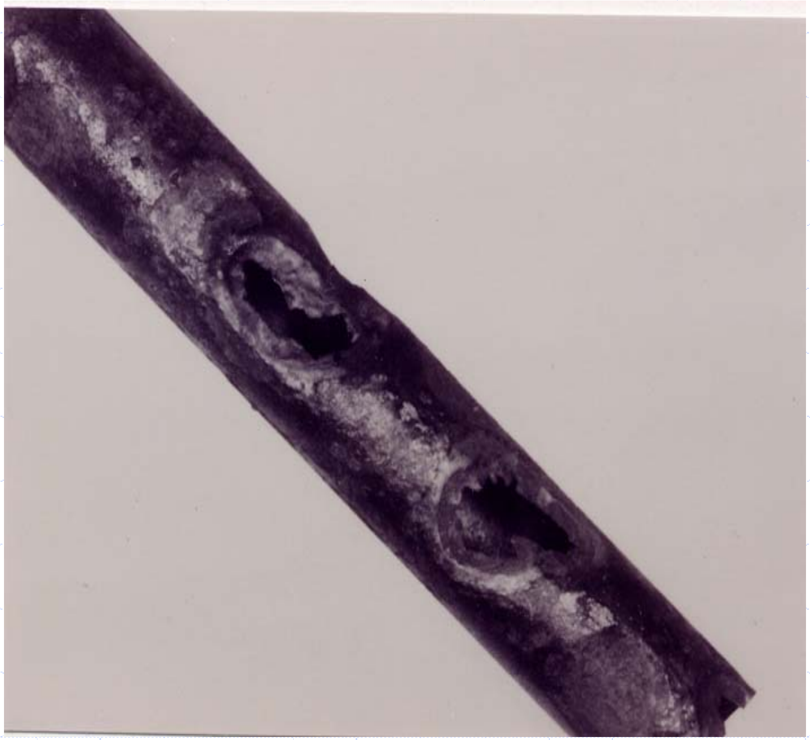
Latest Generation

- Microalloying
  - Small Alloying Additions <0.2%
  - Rare Earth Elements
    - Lanthanum
    - Cerium
    - Yttrium
  - Nitrogen
  - Boron
- Mechanical Alloying
  - Oxide Dispersion Strengthened (ODS)
  - Produced from powder metal

Latest Generation

- Micro Alloying
  - RA 253 MA (Ce)
  - RA 353 MA (Ce)
  - Haynes 214 (Y)
    - Also High Al Content
  - RA 602 CA (Y)
    - Also High Al Content
  - Haynes 230 (La)
    - Also W, B
  - HR-120
    - B, N Strengthened
- Mechanical Alloying
  - Nickel Base
    - MA754
    - MA758
  - Iron Based
    - MA956
    - Kanthal APM
    - PM 2000

Temperature Limitations



310SS at 2100F

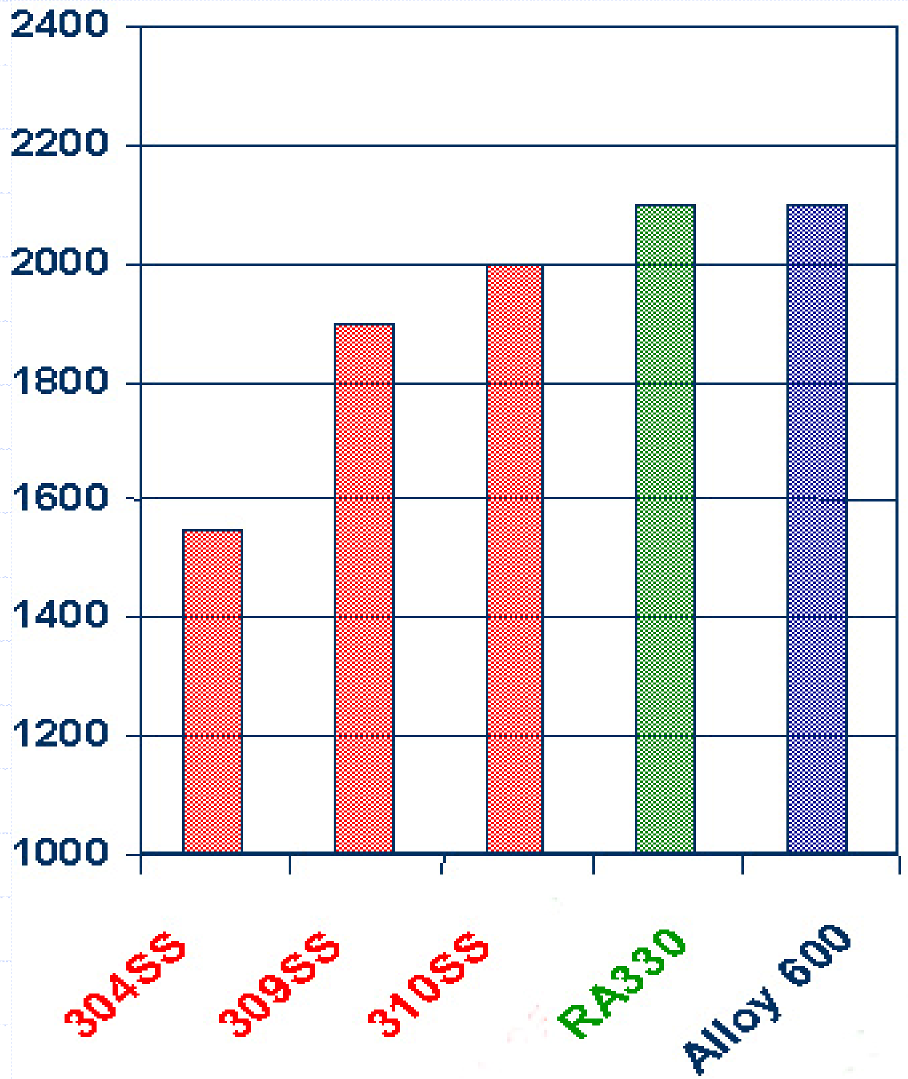
- All alloys have their limits.
- Limiting Factors
  - Oxidation
    - Not melting point, Yet?
  - Strength
  - Embrittlement

Common Failure Modes

- Wastage
  - Oxidation
  - Metal Dusting (Catastrophic Carburization)
  - Sulfidation
  - Halogens/Molten Salt Attack
- Moderate to Low Strength
  - Creep Deformation
  - Distortion
- Brittle Fracture
  - Secondary Phases
  - Carburization
  - Grain Growth

Temperature Limits (ºF), Air

Ni-Cr-Fe Alloys



Extending Oxidation Limits

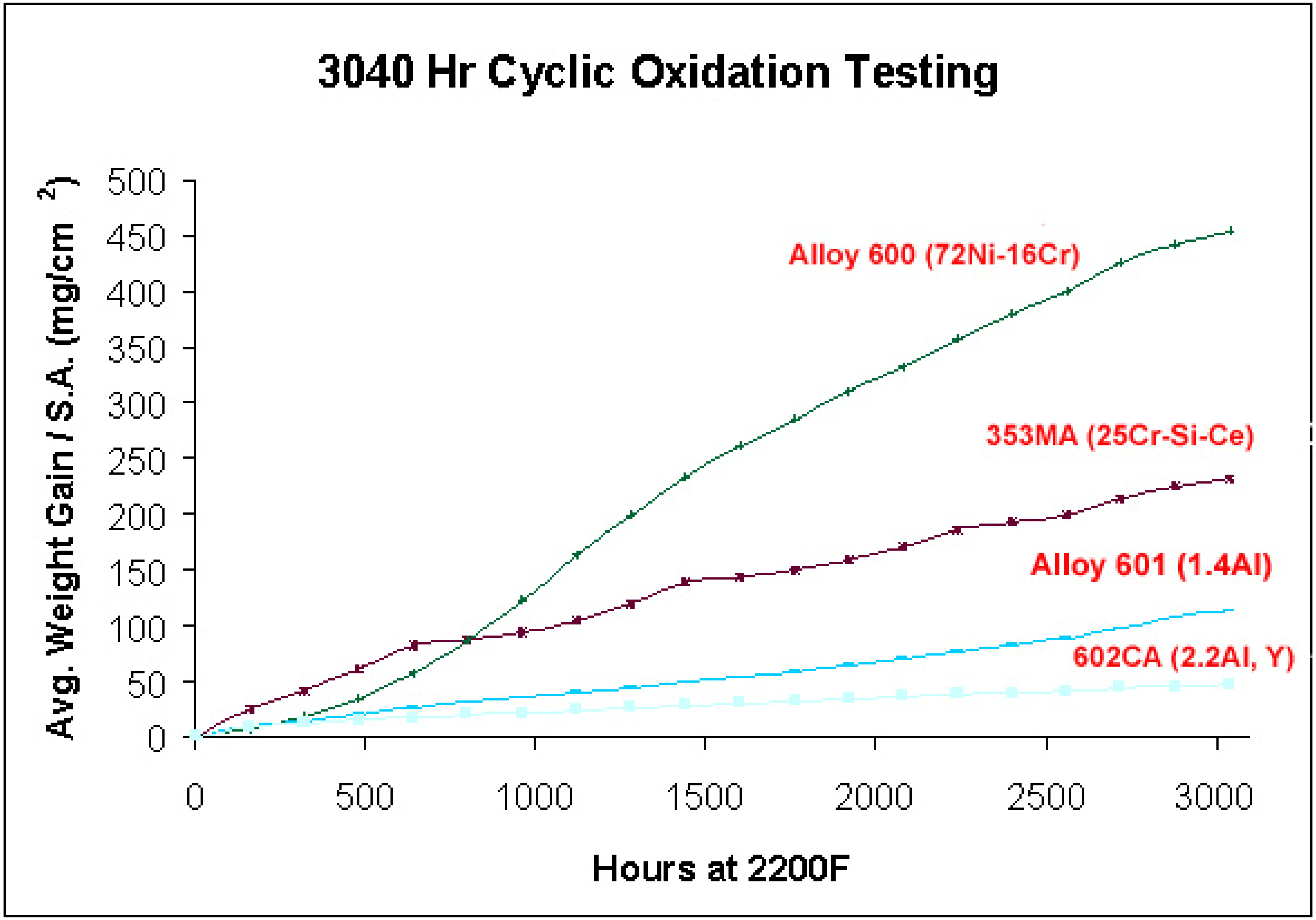
- Oxidation Limits
  - Minor Alloying Elements
    - Aluminum
    - Silicon
  - Micro Alloying Elements
    - Rare Earths
      - Yttrium, Cerium, Lanthanum

Alloying with Aluminum

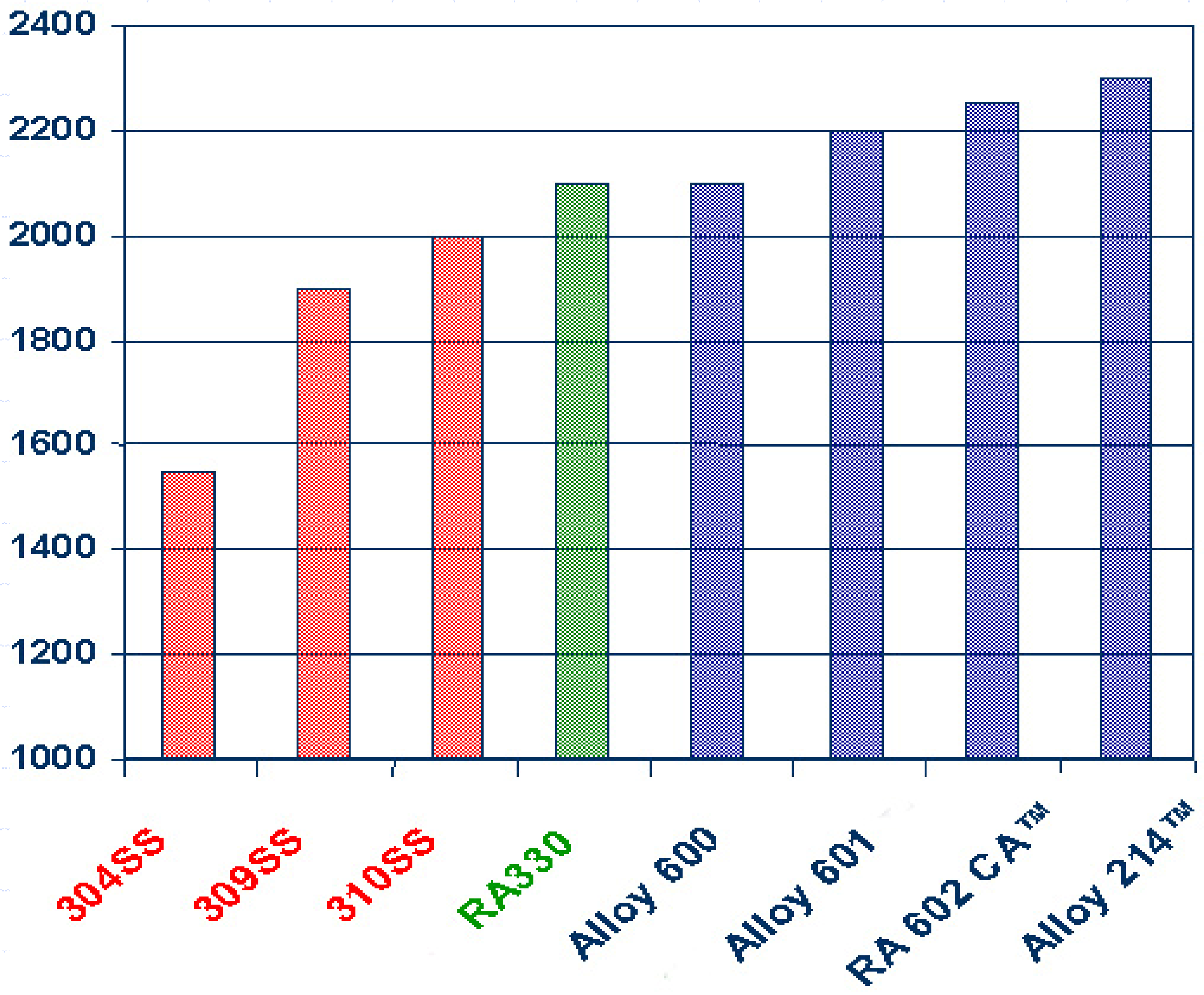
- Wrought
  - Alloy 601 (1.4%)
  - RA 602 CA (2.2%)
    - Micro Alloyed with 0.1% Yttrium
  - Haynes 214 (4.5%)
    - Micro Alloyed with 0.005% Yttrium
- Castings
  - Nickel Aluminides
    - 8-12% Aluminum
- Iron Based -ODS
  - MA956 (4.5%)
    - Mechanically Alloyed with 0.5% Y_2O_3
  - Kanthal APM (5.8%)
  - PM 2000 (5.5%)
    - Mechanically Alloyed with 0.5% Y_2O_3

Scaling Resistance
Cycled between Ambient and 2200°F weekly.

2200°F Testing



Suggested Temperature Limits



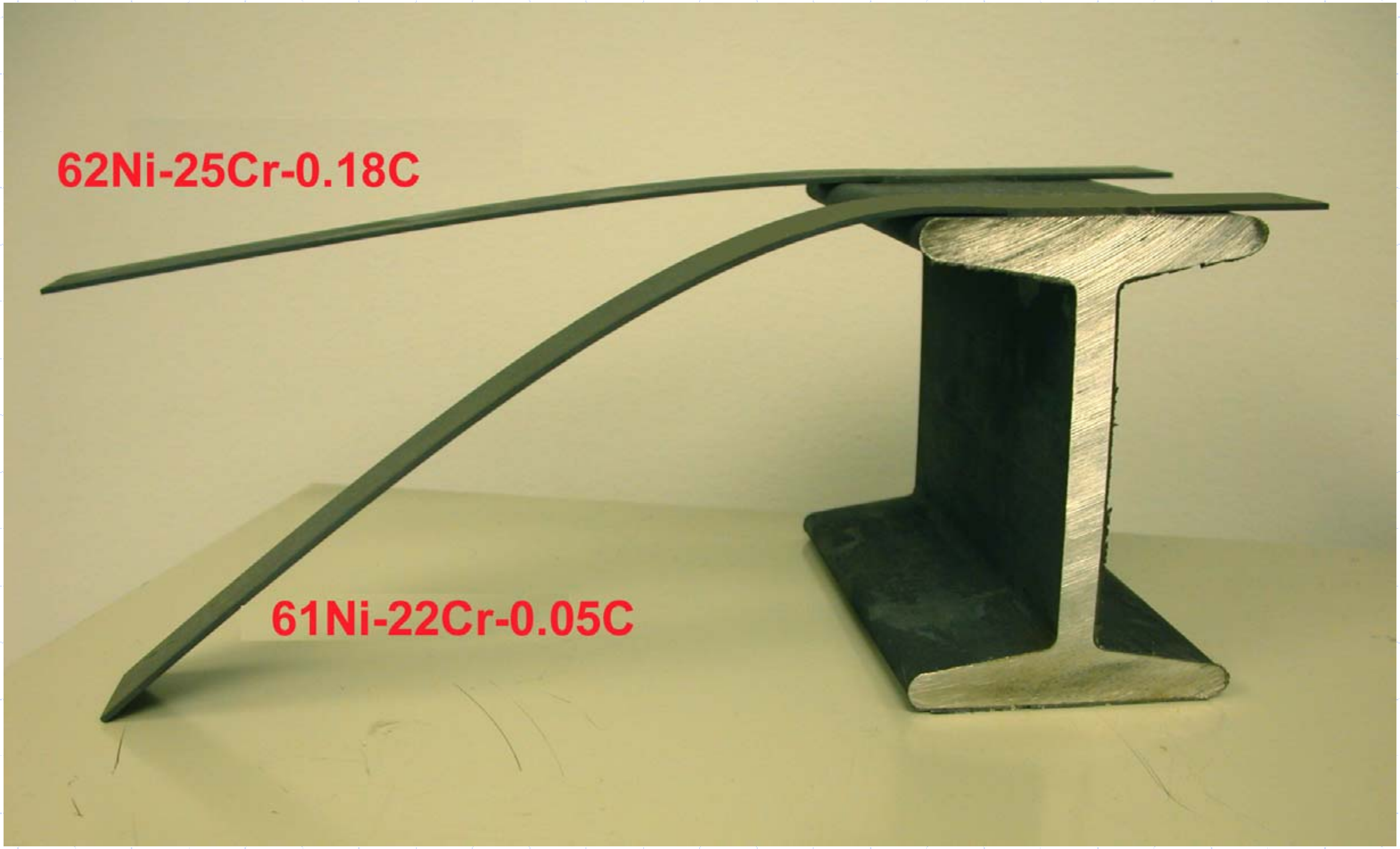
Hurdles to Widespread Adoption

- Higher Aluminum Content Nickel Alloys
  - More prone to hot cracking during welding
    - MIG/TIG may require special shield gases
    - Tighter control on heat input
- Potential for Strain Age Cracking
  - 600°C range

Strengthening

- Carbon
  - RA 602 CA
- Nitrogen
  - RA 353 MA
- Boron
  - HR-120
- Cobalt
  - HR-160
- Molybdenum
  - Hastelloy X
- Aluminum + Titanium
  - Incoloy 800HT
- Tungsten
  - Haynes 230
- Coarse Grains
  - Casting Alloys
  - H Grades
- Mechanical Alloying
  - Yttria

Effect of Carbon On Strength



Strength – 10,000 Hours Rupture, psi

Alloy	Strength	1600F	1800F	1900F	2000F
RA330		1700	630	400	280
800HT	CG Al + Ti	3500	1200	-	-
RA 353 MA	Nitrogen	2600	1300	930	680
HR-120	N, B, Co, Mo, W, Cb	5600	1900	800	
HT (Cast)	CG, High C	3700	1700		

All Alloys 32-37% Nickel Nominally

Average 1000 hour Rupture, psi

Alloy	Strength	1600F	1800F	2000F
Alloy 601		4300	2100	1000
MA754*	ODS	22900	18700	13600

*Longitudinal

Ductility

			High Temperature Phases			
Alloy	Strength	Elongation	885F	Sigma	Strain Age	Nitrides
RA330		48%	No	No	No	No
800HT	CG Al + Ti	48%	No	No	Yes	No
RA 353 MA	Nitrogen	48%	No	Yes	No	Yes
HR-120	N, B, Co, Mo, W, Cb	48%	No	Yes	Yes	Yes
Cast HT	CG, High C	10%	No	No	No	No
446 SS		33%	Yes	Yes	No	No
MA956	Mech Alloy, CG	10%	Yes	Yes	?	?

Hurdles to Widespread Adoption

- Lower Ductility
  - Carbon
  - Boron
  - Nitrogen
  - Coarse Grains
- Cobalt
  - Cost of Raw Material
- ODS
  - Cost of Production
  - Welding
- Reduced Stability
  - Al, Ti, & Cb
    - Strain Aging
  - N, C, B
    - Precipitates
  - Molybdenum
    - Increased Tendency for Sigma

Needs

- Corvette Performance – Chevette Price
  - Price is always foremost consideration
    - Improved Production Methods
    - Leaner Alloying
- Predictability in Service
  - Trailblazers
    - Data, Data, More Data
    - Detailed In Service Performance Data
    - Long Term Ductility

Needs

- Ease of Fabrication
  - Low Ductility
  - Weldability
  - Requirement for Heat Treatment
- Availability
  - Production Needs to Be Reliable
  - Material Available When Opportunities Arise